John E. McMurry • Robert C. Fay

General Chemistry: Atoms First

Chapter 6
Mass Relationships in Chemical Reactions

Lecture Notes

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Balancing Chemical Equations

A balanced chemical equation shows that the **law of conservation of mass** is adhered to.

In a **balanced** chemical equation, the numbers and kinds of atoms on both sides of the reaction arrow are identical.

$$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$$

left side:	right side:
2 Na	2 Na
2 Cl	2 Cl

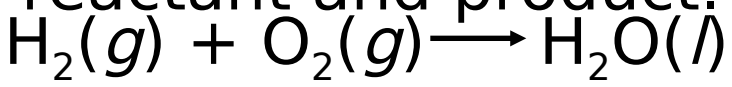
Balancing Chemical Equations

$$Hg(NO_3)_2(aq) + 2KI(aq) \longrightarrow HgI_2(s) + 2KNO_3(aq)$$

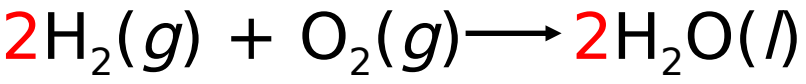
left side:	right side:
1 Hg	1 Hg
2 N	2 I
6 O	2 K
2 K	2 N
2 I	6 O

Balancing Chemical Equations

1. Write the unbalanced equation using the correct chemical formula for each reactant and product.



2. Find suitable coefficients—the numbers placed before formulas to indicate how many formula units of each substance are required to balance the equation.



Balancing Chemical Equations

3. Reduce the coefficients to their smallest whole-number values, if necessary, by dividing them all by a common divisor.

$$4H_2(g) + 2O_2(g) \longrightarrow 4H_2O(l)$$

divide all by 2

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Balancing Chemical Equations

4. Check your answer by making sure that the numbers and kinds of atoms are the same on both sides of the equation.

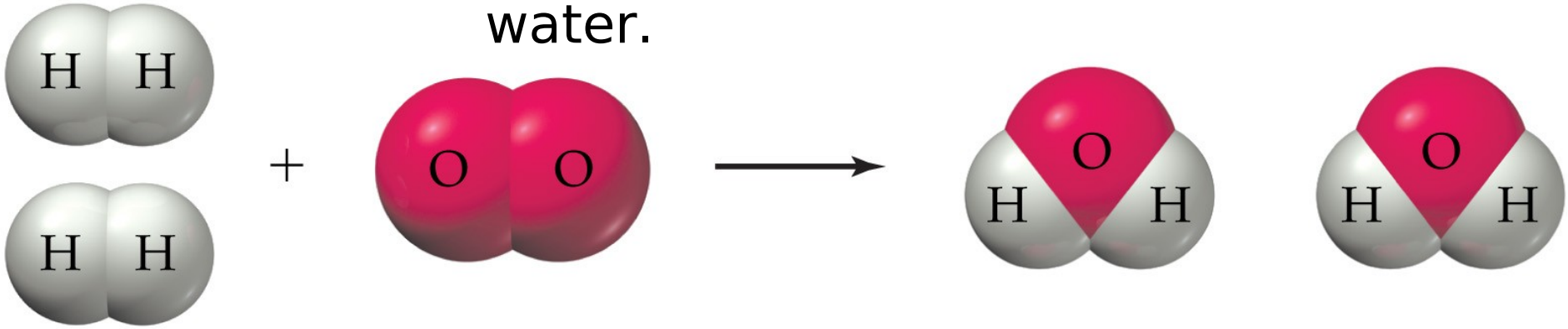
$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

left side:	right side:
4 H	4 H
2 O	2 O

Chemical Symbols on a Different Level

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

microscopic: 2 molecules of hydrogen gas react with 1 molecule of oxygen gas to yield 2 molecules of liquid water.



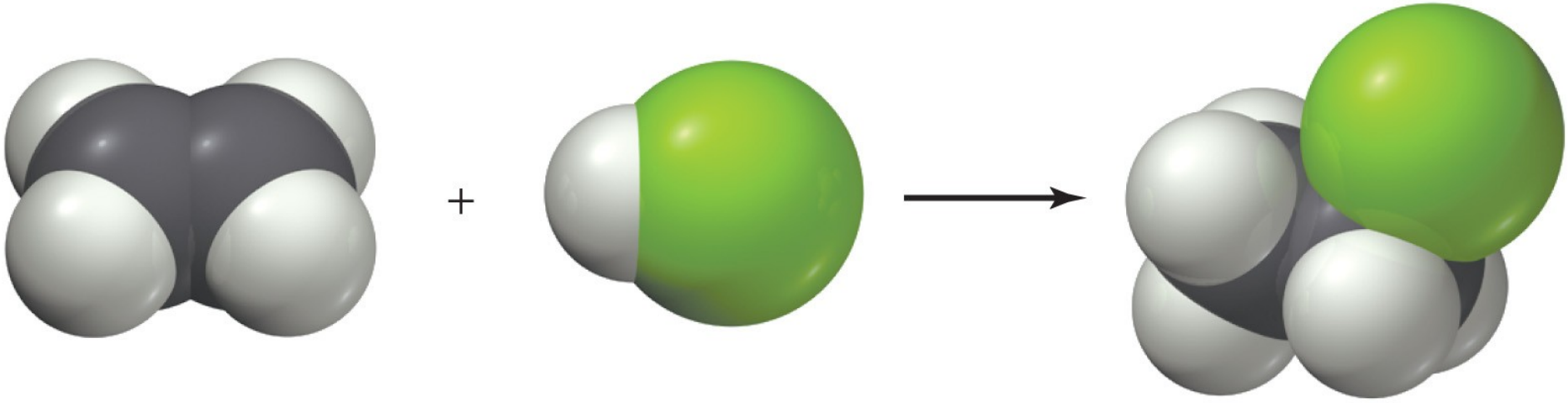
Chemical Symbols on a Different Level

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

microscopic: 2 molecules of hydrogen gas react with 1 molecule of oxygen gas to yield 2 molecules of liquid water.

macroscopic: 0.56 kg of hydrogen gas react with 4.44 kg of oxygen gas to yield 5.00 kg of liquid water.

Chemical Arithmetic: Stoichiometry



$C_2H_4(g)$ + $HCl(g)$ → $C_2H_5Cl(l)$

Ethylene + Hydrogen chloride → Ethyl chloride (an anesthetic)

Chemical Arithmetic: Stoichiometry

Molecular Mass: Sum of atomic masses of all atoms in a molecule.

Formula Mass: Sum of atomic masses of all atoms in a formula unit of any compound, molecular or ionic.

C_2H_4: 2(12.0 amu) + 4(1.0 amu) = 28.0 amu

HCl: 1.0 amu + 35.5 amu = 36.5 amu

Chemical Arithmetic: Stoichiometry

One mole of any substance is equivalent to its molecular or formula mass.

C_2H_4: 1 mole = 28.0 g

6.022×10^{23} molecules = 28.0 g

HCl: 1 mole = 36.5 g

6.022×10^{23} molecules = 36.5 g

Chemical Arithmetic: Stoichiometry

How many moles of chlorine gas, Cl_2, are in 25.0 g?

$$25.0\ g\ Cl_2 \times \frac{1\ mol\ Cl_2}{70.9\ g\ Cl_2} = 0.353\ mol\ Cl_2$$

Chemical Arithmetic: Stoichiometry

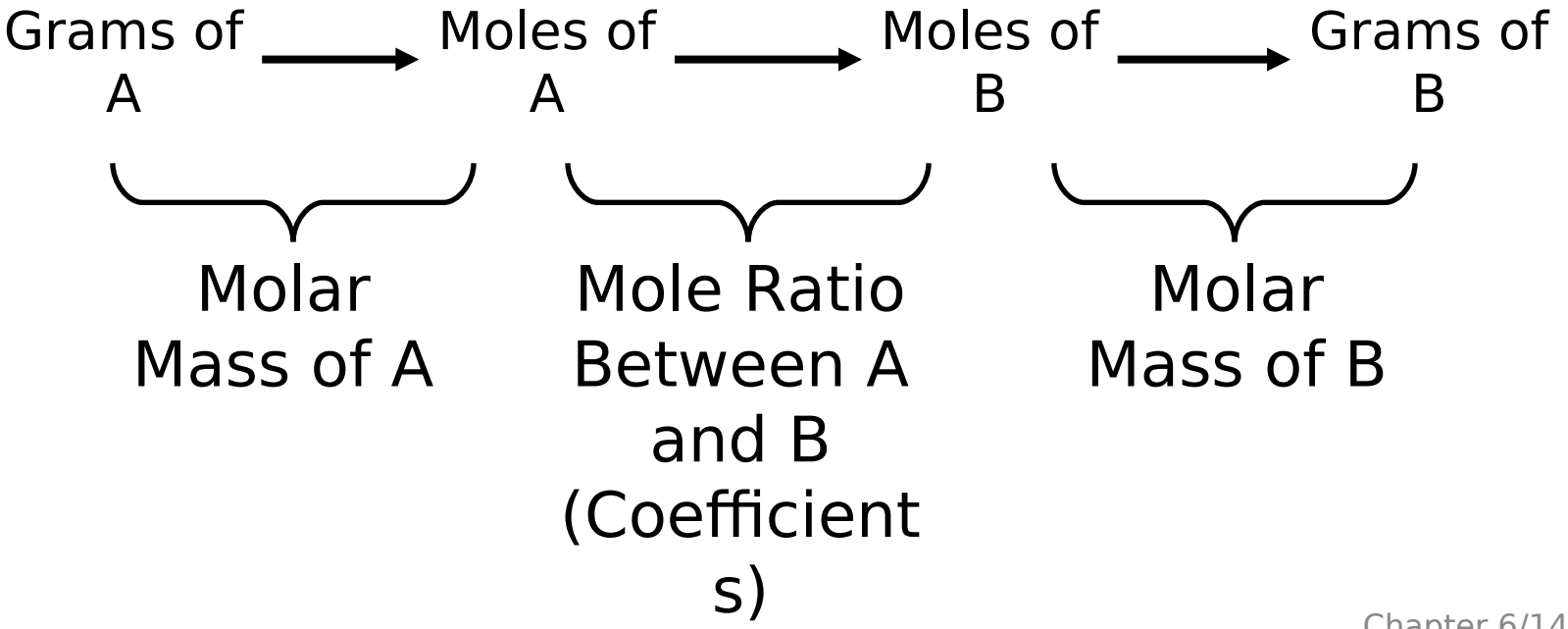
How many grams of sodium hypochlorite, NaOCl, are in 0.705 mol?

$$0.705 \text{ mol NaOCl} \times \frac{40.0 \text{ g NaOCl}}{1 \text{ mol NaOCl}} = 28.2 \text{ g NaOCl}$$

Chemical Arithmetic: Stoichiometry

Stoichiometry: The relative proportions in which elements form compounds or in which substances react.

$$aA + bB \longrightarrow cC + dD$$

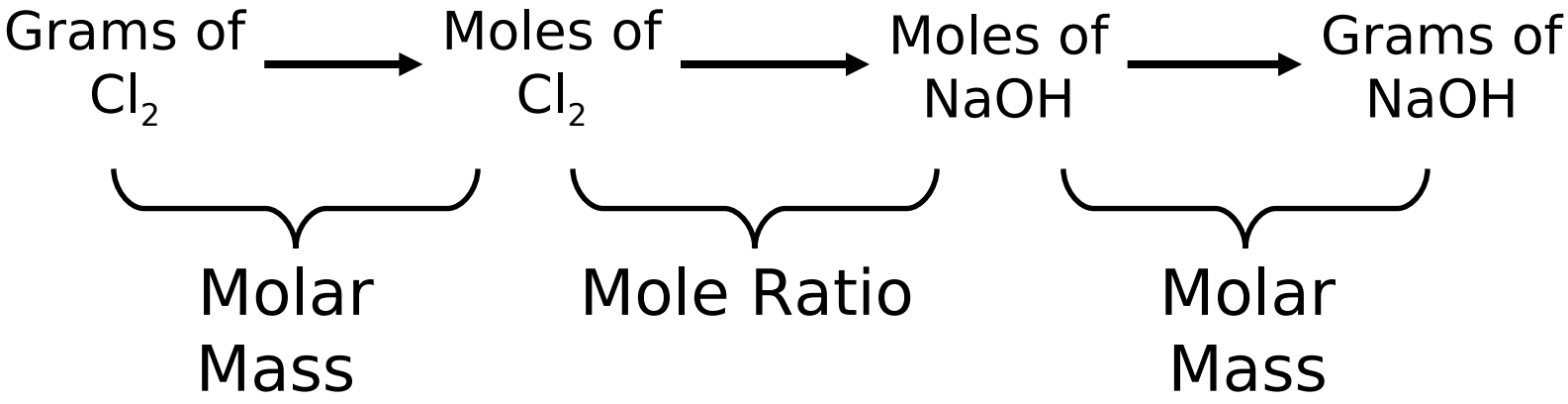


Chemical Arithmetic: Stoichiometry

Aqueous solutions of sodium hypochlorite (NaOCl), best known as household bleach, are prepared by reaction of sodium hydroxide with chlorine gas:

$$2NaOH(aq) + Cl_2(g) \longrightarrow NaOCl(aq) + NaCl(aq) + H_2O(l)$$

How many grams of NaOH are needed to react with 25.0 g Cl_2?



Chemical Arithmetic: Stoichiometry

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$$2NaOH(aq) + Cl_2(g) \longrightarrow NaOCl(aq) + NaCl(aq) + H_2O(l)$$

How many grams of NaOH are needed to react with 25.0 g Cl_2?

$$25.0\ g\ Cl_2 \times \frac{1\ mol\ Cl_2}{70.9\ g\ Cl_2} \times \frac{2\ mol\ NaOH}{1\ mol\ Cl_2} \times \frac{40.0\ g\ NaOH}{1\ mol\ NaOH}$$

$$= 28.2\ g\ NaOH$$

Yields of Chemical Reactions

Actual Yield – The amount actually formed in a reaction.

Theoretical Yield – The amount predicted by calculations.

$$\textbf{Percent Yield} = \frac{\text{Actual yield of product}}{\text{Theoretical yield of product}} \times 100\%$$

Reactions with Limiting Amounts of Reactants

Limiting Reactant: The reactant that is present in limiting amount. The extent to which a chemical reaction takes place depends on the limiting reactant.

Excess Reactant: Any of the other reactants still present after determination of the limiting reactant.

Reactions with Limiting Amounts of Reactants

At a high temperature, ethylene oxide reacts with water to form ethylene glycol, which is an automobile antifreeze and a starting material in the preparation of polyester polymers:

$$C_2H_4O(aq) + H_2O(l) \longrightarrow C_2H_6O_2(l)$$

Because water is so cheap and abundant, it is used in excess when compared to ethylene oxide. This ensures that all of the relatively expensive ethylene oxide is entirely consumed.

Reactions with Limiting Amounts of Reactants

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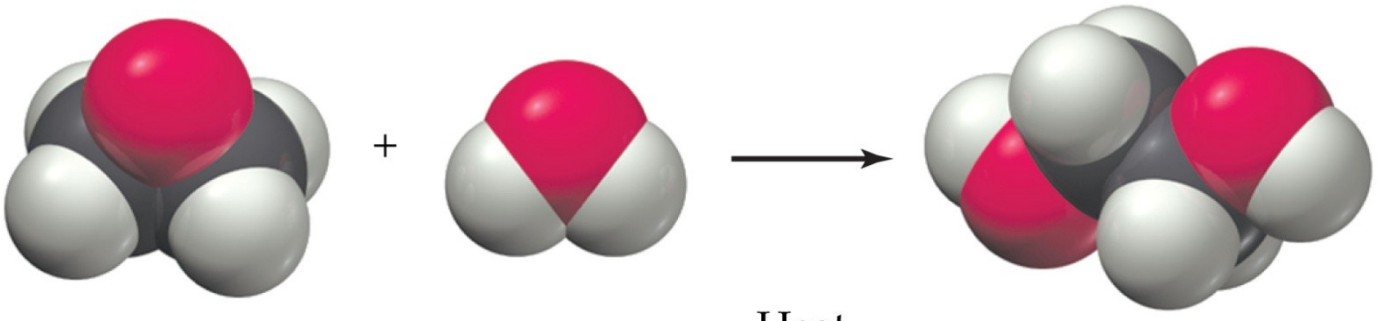

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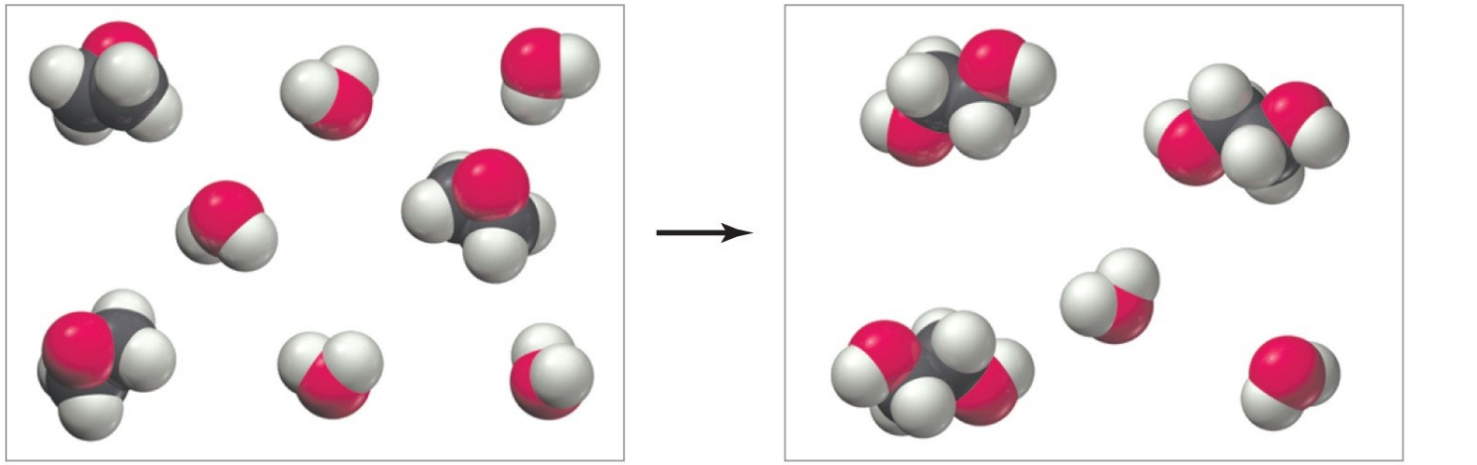
If 3 moles of ethylene oxide react with 5 moles of water, which reactant is limiting and which reactant is present in excess?

Reactions with Limiting Amounts of Reactants

At a high temperature, ethylene oxide reacts with water to form ethylene glycol, which is an automobile antifreeze and a starting material in the preparation of polyester polymers:

$$C_2H_4O(aq) + H_2O(l) \longrightarrow C_2H_6O_2(l)$$



Reactions with Limiting Amounts of Reactants

Lithium oxide is used aboard the space shuttle to remove water from the air supply according to the equation:

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

If 80.0 g of water are to be removed and 65.0 g of Li_2O are available, which reactant is limiting? How many grams of excess reactant remain? How many grams of LiOH are produced?

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

Which reactant is limiting?

Amount of H_2O that will react with 65.0 g Li_2O:

$$65.0 \text{ g } Li_2O \times \frac{1 \text{ mol } Li_2O}{29.9 \text{ g } Li_2O} \times \frac{1 \text{ mol } H_2O}{1 \text{ mol } Li_2O} = 2.17 \text{ moles } H_2O$$

Amount of H_2O given:

$$80.0 \text{ g } H_2O \times \frac{1 \text{ mol } H_2O}{18.0 \text{ g } H_2O} = \boxed{4.44 \text{ moles } H_2O}$$

Li_2O is limiting

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

How many grams of excess H_2O remain?

$$2.17 \text{ mol } H_2O \times \frac{18.0 \text{ g } H_2O}{1 \text{ mol } H_2O} = 39.1 \text{ g } H_2O \text{ (consumed)}$$

$$80.0 \text{ g } H_2O - 39.1 \text{ g } H_2O = 40.9 \text{ g } H_2O$$

initial consumed **remaining**

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

How many grams of LiOH are produced?

$$2.17 \text{ mol } H_2O \times \frac{2 \text{ mol LiOH}}{1 \text{ mol } H_2O} \times \frac{23.9 \text{ g LiOH}}{1 \text{ mol LiOH}} = \boxed{104 \text{ g LiOH}}$$

Concentrations of Reactants in Solution: Molarity

Molarity (M): The number of moles of a substance dissolved in each liter of solution. In practice, a solution of known molarity is prepared by weighing an appropriate amount of solute, placing it in a container called a volumetric flask, and adding enough solvent until an accurately calibrated final volume is reached.

Solution: A homogeneous mixture.

Solute: The dissolved substance in a solution.

Solvent: The major component in a solution.

A measured number of moles of solute is placed in a volumetric flask.

Enough solvent is added to dissolve the solute by swirling.

Further solvent is added to reach the calibration mark on the neck of the flask, and the solution is shaken until uniform.

Concentrations of Reactants in Solution: Molarity

Molarity converts between mole of solute and liters of solution:

$$\text{Molarity} = \frac{\text{Moles of solute}}{\text{Liters of solution}}$$

1.00 mol of sodium chloride placed in enough water to make 1.00 L of solution would have a concentration equal to:

$$\frac{1.00 \text{ mol}}{1.00 \text{ L}} = 1.00 \frac{\text{mol}}{\text{L}} \text{ or } 1.00 \text{ M}$$

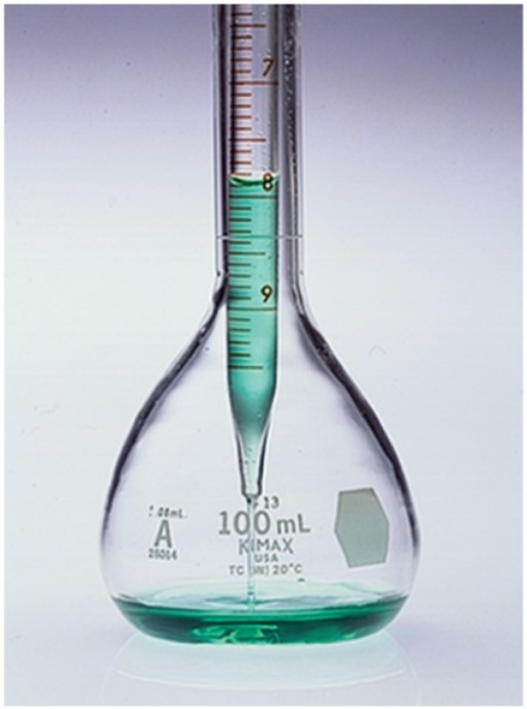
Concentrations of Reactants in Solution: Molarity

How many grams of solute would you use to prepare 1.50 L of 0.250 M glucose, $C_6H_{12}O_6$?

Molar mass $C_6H_{12}O_6$ = 180.0 g/mol

$$1.50\ \text{L} \times \frac{0.250\ \text{mol}}{1\ \text{L}} = 0.275\ \text{mol}$$

$$0.275\ \text{mol} \times \frac{180.0\ \text{g}}{1\ \text{mol}} = \boxed{49.5\ \text{g}}$$



The volume to be diluted is placed in an empty volumetric flask.

Solvent is added to a level just below the calibration mark, and the flask is shaken.

More solvent is added to reach the calibration mark, and the flask is again shaken.

Diluting Concentrated Solutions

concentrated solution + solvent $\longrightarrow$ dilute solution

initial **final**

$$M_i \times V_i = M_f \times V_f$$

Since the number of moles of solute remains constant, all that changes is the volume of solution by adding more solvent.

Diluting Concentrated Solutions

Sulfuric acid is normally purchased at a concentration of 18.0 M. How would you prepare 250.0 mL of 0.500 M aqueous H_2SO_4?

$M_i = 18.0\ M$ $\qquad$ $M_f = 0.500\ M$

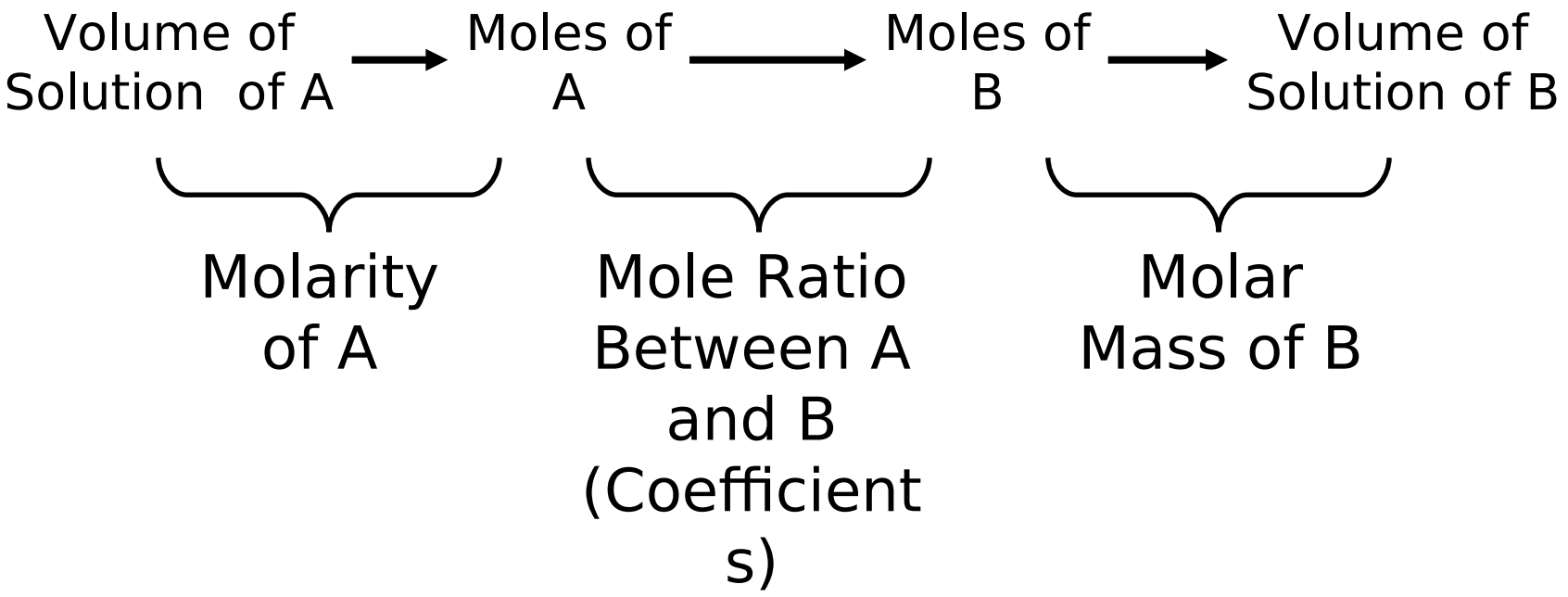
$V_i = ?\ mL$ $\qquad$ $V_f = 250.0\ mL$

$$V_i = \frac{M_f}{M_i} \times V_f = \frac{0.500\ M}{18.0\ M} \times 250.0\ mL = \boxed{6.94\ mL}$$

Add 6.94 mL 18.0 M sulfuric acid to enough water to make 250.0 mL of 0.500 M solution.

Solution Stoichiometry

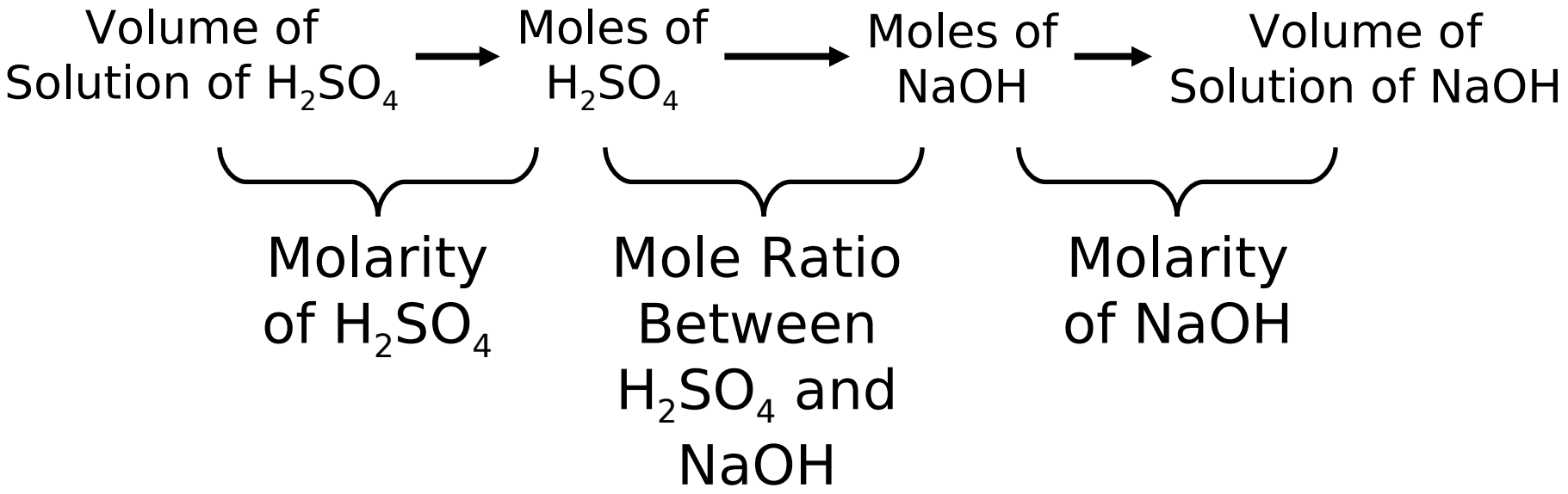
$$aA + bB \longrightarrow cC + dD$$


Volume of Solution of A
Moles of A
Moles of B
Volume of Solution of B
Molarity of A
Mole Ratio Between A and B (Coefficients)
Molar Mass of B

Solution Stoichiometry

What volume of 0.250 M H_2SO_4 is needed to react with 50.0 mL of 0.100 M NaOH?

$$H_2SO_4(aq) + 2NaOH(aq) \longrightarrow Na_2SO_4(aq) + 2H_2O(l)$$


Volume of Solution of H_2SO_4
Moles of H_2SO_4
Moles of NaOH
Volume of Solution of NaOH
Molarity of H_2SO_4
Mole Ratio Between H_2SO_4 and NaOH
Molarity of NaOH

Solution Stoichiometry

$$H_2SO_4(aq) + 2NaOH(aq) \longrightarrow Na_2SO_4(aq) + 2H_2O(l)$$

Moles of NaOH available:

$$50.0 \text{ mL NaOH} \times \frac{0.100 \text{ mol}}{1 \text{ L}} \times \frac{1 \text{ L}}{1000 \text{ mL}} = 0.00500 \text{ mol NaOH}$$

Volume of H_2SO_4 needed:

$$0.00500 \text{ mol NaOH} \times \frac{1 \text{ mol } H_2SO_4}{2 \text{ mol NaOH}} \times \frac{1 \text{ L solution}}{0.250 \text{ mol } H_2SO_4} \times \frac{1000 \text{ mL}}{1 \text{ L}}$$

$$10.0 \text{ mL solution (0.250 M } H_2SO_4)$$

Titration

Titration: A procedure for determining the concentration of a solution by allowing a carefully measured volume to react with a solution of another substance (the standard solution) whose concentration is known.

$$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + 2H_2O(l)$$

Once the reaction is complete you can calculate the concentration of the unknown solution.

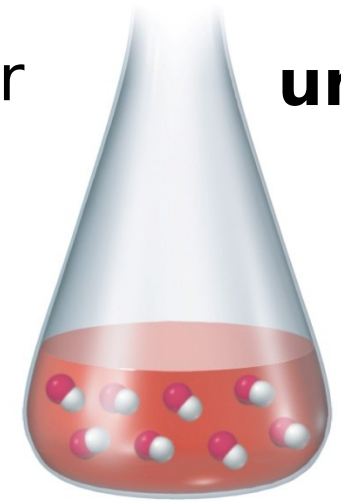
How can you tell when the reaction is complete?

Titration

buret

standard solution
(known concentration)

Erlenmeyer flask



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unknown concentration solution

An indicator is added which changes color once the reaction is complete

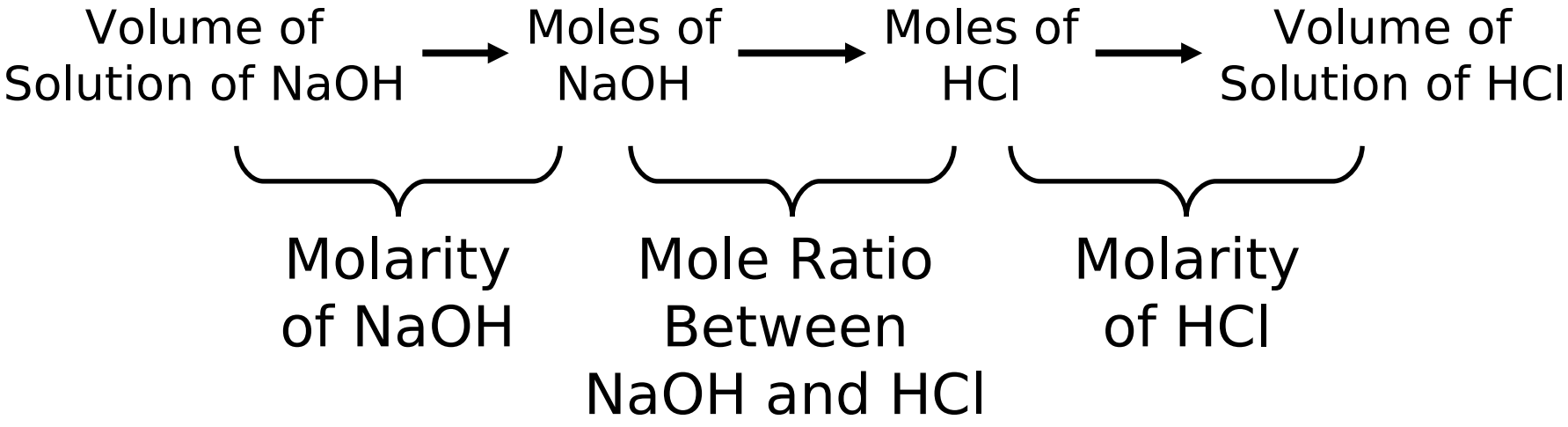
A measured volume of acid solution is placed in a flask, and phenolphthalein indicator is added.

Base solution of known concentration is added from a buret until the indicator changes color. Reading the volume of base from the buret allows calculation of the acid concentration.

Titration

48.6 mL of a 0.100 M NaOH solution is needed to react with 20.0 mL of an unknown HCl concentration. What is the concentration of the HCl solution?

$$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + 2H_2O(l)$$


Volume of Solution of NaOH
Moles of NaOH
Moles of HCl
Volume of Solution of HCl
Molarity of NaOH
Mole Ratio Between NaOH and HCl
Molarity of HCl

Titration

$$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + 2H_2O(l)$$

Moles of NaOH available:

$$48.6 \text{ mL NaOH} \times \frac{0.100 \text{ mol}}{1 \text{ L}} \times \frac{1 \text{ L}}{1000 \text{ mL}} = 0.00486 \text{ mol NaOH}$$

Moles of HCl reacted:

$$0.00486 \text{ mol NaOH} \times \frac{1 \text{ mol HCl}}{1 \text{ mol NaOH}} = 0.00486 \text{ mol HCl}$$

Concentration of HCl solution:

$$\frac{0.00486 \text{ mol HCl}}{20.0 \text{ mL solution}} \times \frac{1000 \text{ mL}}{1 \text{ L}} = \boxed{0.243 \text{ M HC}}$$

Percent Composition and Empirical Formulas

Percent Composition: Expressed by identifying the elements present and giving the mass percent of each.

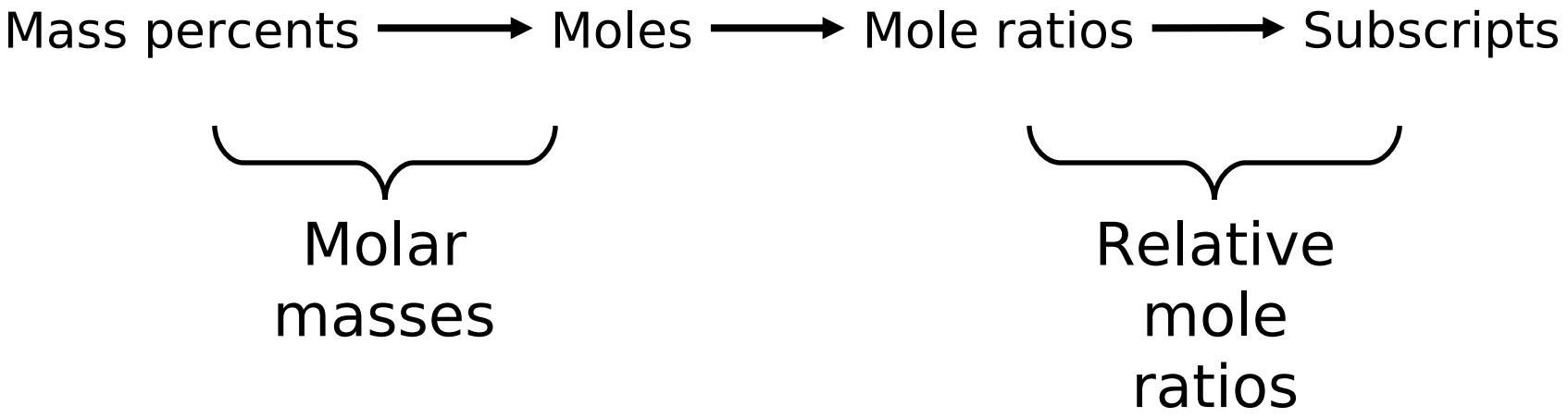
Empirical Formula: It tells the smallest whole-number ratios of atoms in a compound.

Molecular Formula: It tells the actual numbers of atoms in a compound. It can be either the empirical formula or a multiple of it.

$$\text{Multiple} = \frac{\text{Molecular mass}}{\text{Empirical formula mass}}$$

Percent Composition and Empirical Formulas

A colorless liquid has a composition of 84.1 % carbon and 15.9 % hydrogen by mass. Determine the empirical formula. Also, assuming the molar mass of this compound is 114.2 g/mol, determine the molecular formula of this compound.



Percent Composition and Empirical Formulas

Assume 100.0 g of the substance:

Mole of carbon:

$$84.1\ \text{g C} \times \frac{1\ \text{mol C}}{12.0\ \text{g C}} = 7.01\ \text{mol C}$$

Mole of hydrogen:

$$15.9\ \text{g H} \times \frac{1\ \text{mol H}}{1.0\ \text{g H}} = 15.9\ \text{mol H}$$

Percent Composition and Empirical Formulas

Empirical formula:

$C_{7.01}H_{15.9}$

smallest value for the ratio

$$C_{\frac{7.01}{7.01}}H_{\frac{15.9}{7.01}} = C_1H_{2.27}$$

$C_1H_{2.27}$

need whole numbers

$$C_{1x4}H_{2.27x4} = \boxed{C_4H_9}$$

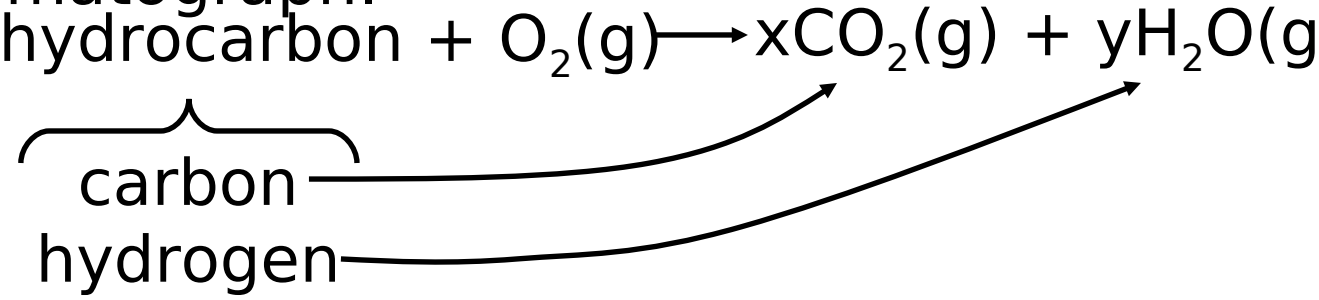
Molecular formula:

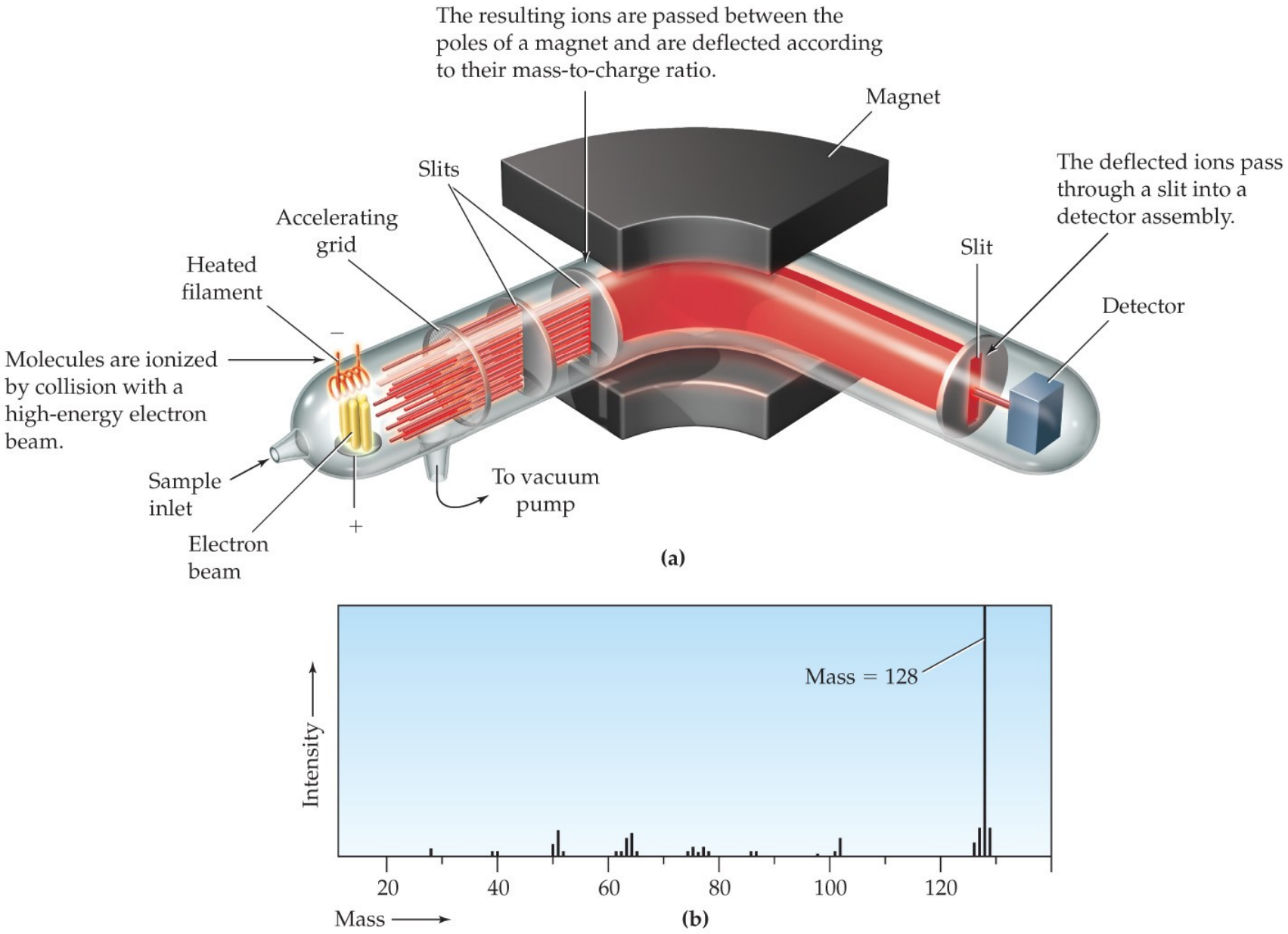
$$\text{multiple} = \frac{114.2}{57.0} = 2$$

$$C_{4x2}H_{9x2} = \boxed{C_8H_{18}}$$

Determining Empirical Formulas: Elemental Analysis

Combustion Analysis: A compound of unknown composition (containing a combination of carbon, hydrogen, and possibly oxygen) is burned with oxygen to produce the volatile combustion products CO_2 and H_2O, which are separated and weighed by an automated instrument called a gas chromatograph.




The resulting ions are passed between the poles of a magnet and are deflected according to their mass-to-charge ratio.
Magnet
Slits
Accelerating grid
Heated filament
The deflected ions pass through a slit into a detector assembly.
Slit
Detector
Molecules are ionized by collision with a high-energy electron beam.
Sample inlet
To vacuum pump
Electron beam
(a)
Mass = 128
Intensity
20
40
60
80
100
120
Mass
(b)